Ar ion beam irradiation effects on magnetostriction of Tb-Fe thin film

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Abstract

$TbFe_2$ film prepared by a flash evaporation system onto Si(100) or polyamide substrate have been irradiated with different Ar ion doses at zero, 1.3×10^{17} and 2.7×10^{17} ions/cm^2 and at 10 kV. Magnetostrictive properties of $TbFe_2$ film with disordered structure, saturated magnetostriction and magnetostrictive susceptibility, improved by Ar ion beam irradiation due to increasing of in-plane compressive stress.

1. INTRODUCTION

The giant magnetostrictive films exhibit promising high applicability to devices for micro-machines, sensor systems and surface acoustic wave filters[1] due to high response velocity and huge stress. For these applications, high magnetostrictive susceptibilities with appropriate small hysteresis at low magnetic field are required. Since 1990, we have investigated systematically the magnetostrictive properties of the films such as the $TbFe_2$, $DyFe_2$, and $(Tb,Dy)Fe_2$ compounds using different processes of thin film formation systems[2], i.e., flash evaporation[3-7], ion beam sputtering[8], ion plating[9], electron beam evaporation[9], and magnetron sputtering[10]. We previously reported that RFe_2 (R=rare earth elements) films include high concentration of gases such as oxygen, H_2O, CO, or CO_2 in a used system during a film formation process, in particularly, oxygen markedly affects magnetic and magnetostrictive properties (Uchida *et al*., 2002)[2]. The giant magnetostrictive films are affected by vacuum condition, concentration, microstructure, and internal stress. In particularly internal stress often dominates the magnetostrictive properties. Therefore, many studies have done about internal stress (Schatz *et al*., 1994[11], Xu *et al*., 2001[12]). Wada *et al.* (1996) have reported that Tb-Dy-Fe (a popular giant magnetostrictive material) thin film prepared by ion beam sputtering system using Ar may be attributed to the change of internal stress induced by Ar inclusion into the film during the deposition[8]. Nevertheless, due to high costs and technical difficulties, the ion beam sputtering system is only used in laboratory and so on. Thin film has been formed using magnetron sputtering system or CVD. Post-treatment is therefore advantageous to improve magnetostrictive properties by effects ion beam irradiation. However, in giant magnetostrictive film quantitative effects on magnetostrictive characteristics and residual stress inside the film caused by Ar ion beam irradiation have not been clear. In this study, the effect of Ar ion beam irradiation on the magnetic and magnetostrictive characteristics of $TbFe_2$ films was discussed quantitatively.

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2. EXPERIMENTAL

To reveal effects on magnetostriction by Ar ion beam irradiation, the samples were prepared by the flash evaporation system because the system is low energy process[3-7]. Base pressure was 8.8×10^{-5} Pa, and substrate temperature was maintained at ~400 K. The $TbFe_2$ powder pulverized into 40 – 100 μm was evaporated onto substrates by tungsten heater at ~2300 K. The $TbFe_2$ films were deposited on either single crystal Si (100) wafer (0.28mm thick) or polyimide substrate (0.13 mm thick), with deposition rate of 16 nm/sec.

The $TbFe_2$ films prepared by flash evaporation system were irradiated with Ar ion beam. The Ar ion beam irradiation was done by a plasma cathode ion source. The ion source system has been reported elsewhere (Yabe *et al.*, 1987[13]). Vacuum conditions were in the range of 10^{-5} Pa as background and 1.5×10^{-2} Pa as irradiation Ar gas pressure. The Ar ion beam by the potential of 10 kV applied between the ion source and the sample target. The flux was 4.2×10^{14} ions/cm^{2}s. The $TbFe_2$ film was treated with the Ar ion beam at 1.3 or 2.7×10^{17} doses.

The structure of the film was examined by X-ray diffraction (XRD) using Cu Kα radiation. The chemical composition of the film was determined using energy dispersive X-ray spectroscopy (EDX), and the amount of Ar atom implanted to film was determined by thermal desorption spectroscopy (TDS). The magnetization of the film samples were measured using vibrating sample magnetometer (VSM) in the range of plus minus 15 kOe. The magnetostriction of film sample was measured by a bending cantilever beam method[14,15] in parallel direction to the film plane. For the calculation of the magnetostriction an effective Young's modulus of the film was assumed to be 76 GPa (refer Ferromagnetic Materials, vol. 1, 1980[16]). The residual stress inside the film was determined from measurement of bending cantilever method using micrometer (Riethmuller and Benecke,1988[17]).

3. RESULTS AND DISCUSSIONS

3.1. Film composition and quantity of implanted Ar

The composition of the film was $TbFe_2$ and did not varied before and after the Ar ion beam irradiation. A small amount of Ar was observed in the film exposed to Ar ion beam, while no Ar was observed in the as-deposited film (see Fig. 1 and 2). These results indicate that Ar atoms were implanted into the film during ion beam irradiation.

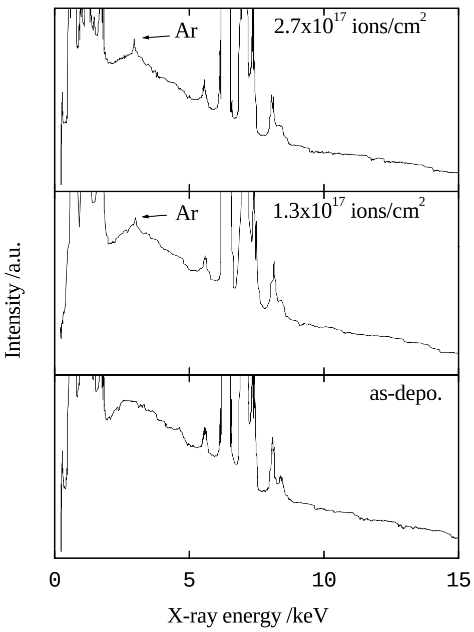

Fig.1. EDX spectra of $TbFe_2$ film exposed to different irradiation doses.

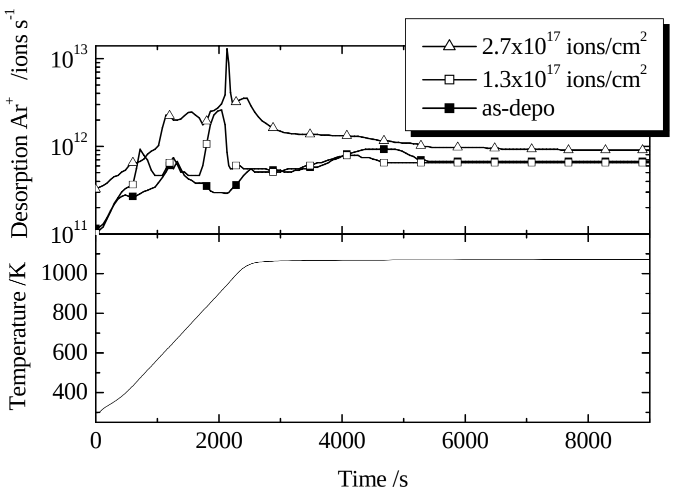

Fig.2. TDS spectra of $TbFe_2$ film exposed to different irradiation doses, and the desorption temperature.

3.2. Film structure

XRD diffraction patterns of $TbFe_2$ film treated with different irradiation doses are shown in Fig. 3. No distinct diffraction peaks from $TbFe_2$ phase were observed in as-deposited sample, suggesting that microstructure of the as-deposited film was expected to be amorphous structure. XRD patterns shown in Fig. 3. indicated that films seem to be composed of extremely fine grains or be in amorphous state. In previous studies, we reported that Tb-Dy-Fe film shows nano-crystalline structure (grain size < 10 nm) when ratio R of vacuum-to-deposition rate in a film formation process is less than 5.0×10^{-4} Pa s nm^{-1} (Wada et al., 1996[5]). The ratio R is defined as p/r, where p is pressure during film formation and r is deposition rate. The ratio R was 5.0×10^{-5} Pa s nm^{-1} in this work, the $TbFe_2$ film could be nano-structured. The result may lead to small magnetostrictive hysteresis because of extremely low magneto-crystalline anisotropy.

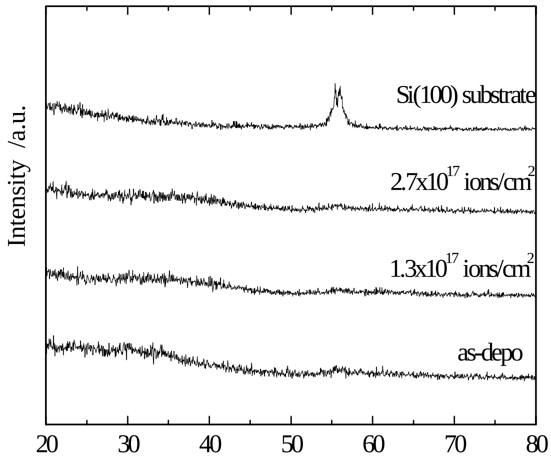

Fig.3. XRD diffraction patterns of $TbFe_2$ films at different Ar ion irradiation doses.

3.3. Magnetic and magnetostrictive characteristics

Figure 4 shows the magnetization hysteresis loops (parallel to the film) of $TbFe_2$ films for the Ar ion irradiation doses of zero, 1.3×10^{17} and 2.7×10^{17} ions/cm^2. Crystalline $TbFe_2$ film has a perpendicular magnetic anisotropy[2]. In all these magnetization measurements, no differences of the saturation magnetization of the film were observed with different Ar ion doses. These samples seem to be affected strongly magneto-shape anisotropy and residual stress due to little magneto-crystalline anisotropy from the disordered structure shown in XRD diffraction patterns.

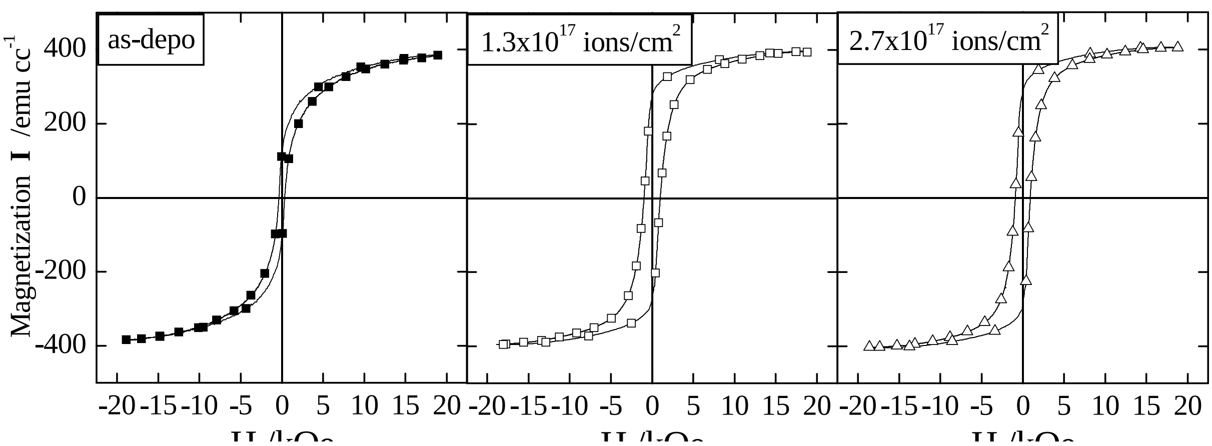

Fig.4. The magnetic hysteresis loops of $TbFe_2$ film at different Ar ion irradiation doses.

Figure 5 shows magnetostriction $\Delta\lambda_{//}$ of $TbFe_2$ films at different Ar ion beam irradiation doses. In all cases the magnetostrictive hysteresis was not found within our experimental precision, but the magnetostriction at 15 kOe of magnetic field increased by Ar ion beam irradiation. These effects may be caused by increasing of the in-plane compression stress inside the film due to Ar ion implantation. As shown in Fig.6, Ar ion implantation yielded increase in magnetostrictive susceptibility in the low magnetic field. The magnetostrictive susceptibility reached the maximum value and decreased with magnetic field. The applied magnetic field giving the maximum value of magnetostrictive susceptibility decreased by Ar ion beam irradiation. Large magnetostrictive susceptibility of $TbFe_2$ film implanted Ar atoms may be induced increasing magnetoelastic energy resulted in change of residual stress inside the film due to Ar ion beam irradiation.

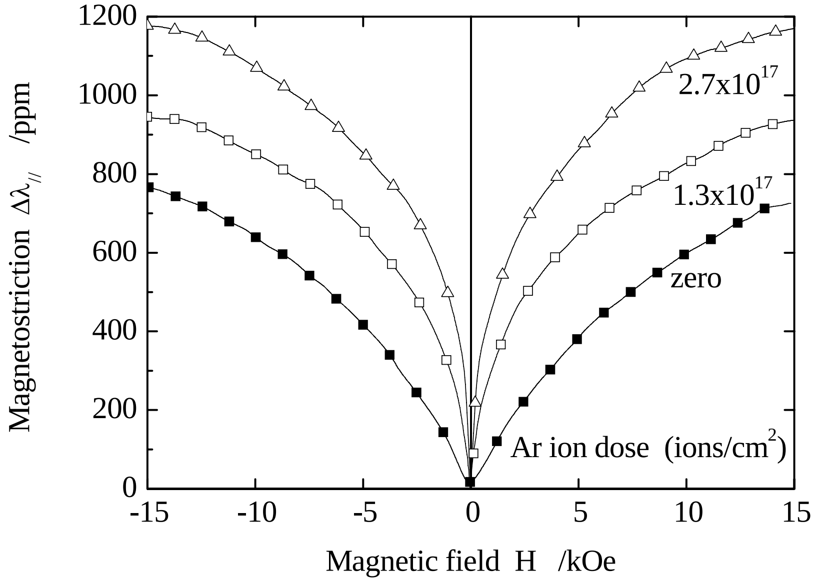

Fig.5. The field dependence of magnetostriction for $TbFe_2$ film exposed to different Ar ion beam irradiation doses.

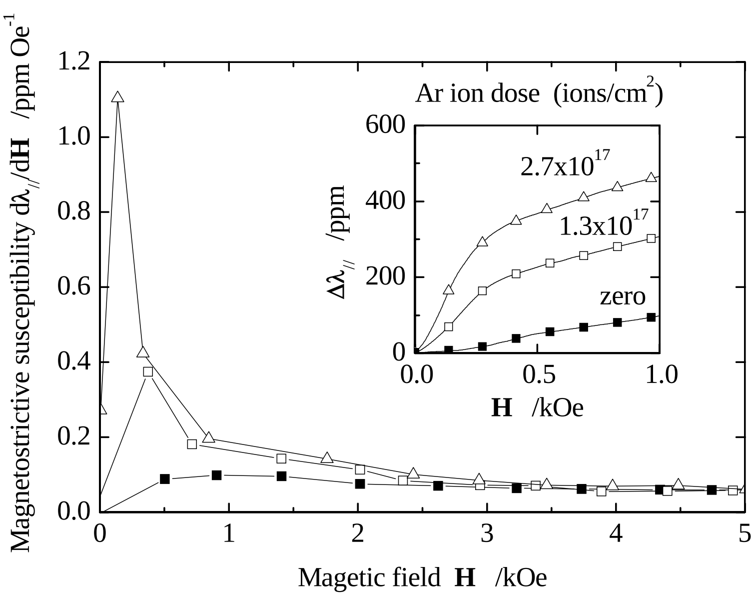

Fig.6. The magnetostrictive susceptibility of $TbFe_2$ film under different Ar ion doses.

3.4. Residual stress

Fig. 7 shows the residual stress of in-plane direction as a function of Ar ion dose. In film material, film receives stress as the result of bending substrate. The residual stress of as-deposited $TbFe_2$ film was calculated with thermal expansion coefficient α (Si single crystal: $4x10^{-6}$ /K, $TbFe_2$ was assumed as $12x10^{-6}$ /K from TbDyFe data of *Ferromagnetic Materials*, 1980[16]). The as-deposited $TbFe_2$ film must have tensile stress in the direction parallel to the film surface due to the fact that thermal contraction of the film is larger than that of Si (100) substrate. The residual stress inside the film varied to compression stress from tensile stress with increasing amount of Ar ion dose, and tends to an exponential decrease in tensile stress. Perry has reported that large changes in residual stress and strain distributions are introduced, which extend well beyond the implanted zone and dense dislocation networks are introduced in an implantation affected zone which extended beyond film thickness ranges about 0.01-2.6 μm (Perry, 1998[18]). In the $TbFe_2$ film the dense dislocation networks at depths beyond the Ar implanted zone most likely caused to increase compressive stress parallel to film plane.

Following Schatz *et al* (1994), films with in-plane anisotropy show high magnetostriction at low fields due to the easy rotation of the spins in the isotropic plane even if the motion of the 180 degree domain walls does not contribute to magnetostriction, but films with perpendicular anisotropy need far higher applied fields to obtain the same in-plane magnetization and magnetostriction and the contribution of all domains to the magnetostriction gives rise to a higher maximum value[11]. However, the $TbFe_2$ film irradiated by Ar ion beam showed large magnetostriction and high magnetostrictive susceptibility. The high magnetostrictive susceptibility is probably caused soft magnetic properties corresponding the disordered structure, following Wada *et al*., 1996[6].

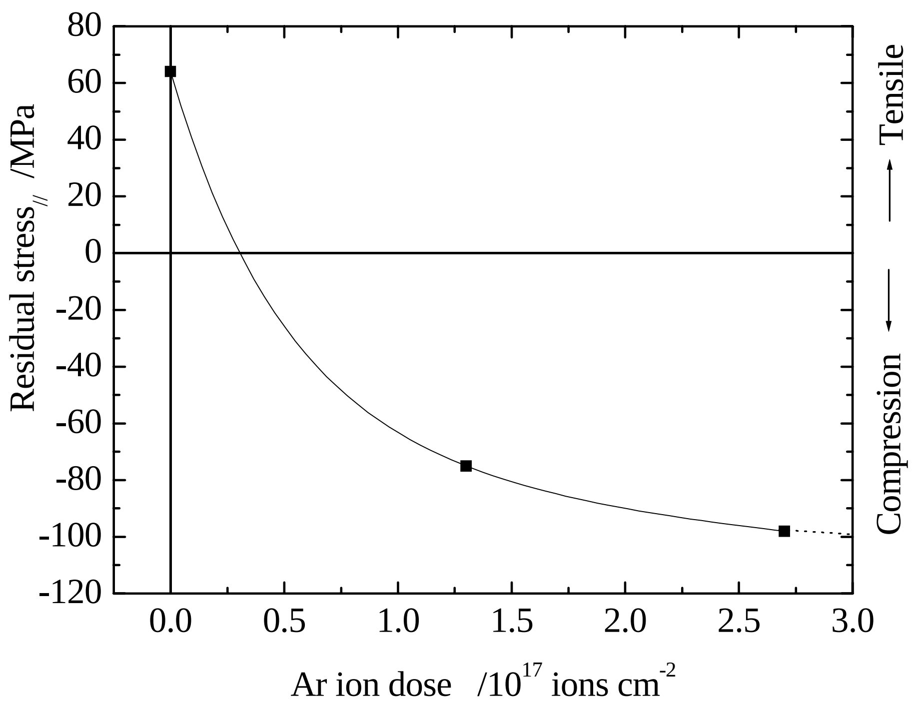

Fig. 7. The residual stress of in-plane direction inside the $TbFe_2$ film as a function of Ar ion dose.

4. CONCLUSIONS

$TbFe_2$ film, deposited onto Si(100) or polyamide substrate by flash evaporation, have been implanted with Ar at different doses. The results indicate that magnetostrictive properties of $TbFe_2$ film with disordered structure, saturated magnetostriction and magnetostrictive susceptibility, can be improved by Ar ion beam irradiation due to increasing of in-plane compressive stress.

5. ACKNOWLEDGEMENT

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